Vision Aid for Power Wheelchair Users

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The sitting posture of power wheelchair (WC) users greatly limits their overall visibility. Without the ability to stand or lean forward, WC users are prevented from peering over most obstacles and into deep containers. A vision aid to raise or extend forward the line of sight of power WC users would be useful in many daily living, educational, and occupational activities. The design of the WC camera was based on the human factor requirements of a quadriplegic WC user and the results of a detailed House of Quality. The development of a pulley and belt-driven linkage system with a digital camera satisfied the top-ranked client and engineering requirements. Comprehensive engineering analyses were also performed to study the strength, safety, and failure modes of the WC camera mechanism. The WC camera provided a range of viewing positions from the front of the WC at eye level to more than 2 ft in front of the WC user's knees at waist level. The solutions to expand visibility of WC users have not been adequately addressed in previous investigations in wheeled mobility.

[DOI: 10.1115/1.3006347]

Keywords: rehabilitation engineering, human factors engineering, power wheelchair, spinal cord injury, quadriplegia/tetraplegia

1 Introduction

The line of sight of wheelchair (WC) users is limited to the sitting position. In contrast, nondisabled persons may adjust their line of sight by positioning their bodies from recumbency to crouching, to standing, and to many positions in between [1,2]. Therefore, power wheelchair users are unable to look upon objects from above or see underneath objects that are lower than their eye height, such as under desks or in lower cabinets. Though, some power WCs can elevate the seat or stand the user to an erect position, this only provides a fraction of the range of eye heights that nondisabled persons can achieve (Fig. 1(*a*)).

When standing, nondisabled persons can lean forward by flexing their ankles and bending at the waist to project their heads beyond their feet, which greatly extends their forward line of sight. Thus, inclining provides the ability to peer over objects, including railings, desks and tabletops, and into deep open containers like boxes, pots, or tanks. In contrast, the forward line of sight of power WC users is restricted. WC users can only bend at the waist when sitting. This generally means that they can only peer over their knees or the sides of their armrests. For high-level quadriplegics, bending at the waist is not possible and their visual fulcrum is even higher at the neck further limiting their line of sight. Additionally, the position of WC users' knees and footrests in front of them is a major impediment to getting near to vertical obstacles—such as a railing or cabinet—to peer over them (Figs. 1(*b*) and 2(*a*)). Often WC users must pull along side of the railing to get a closer look over this obstacle. This posture can cause physical stress over long or repetitive periods of time (Fig. 2(*b*)). The body mechanics of WC use also limits a person's forward reach. Retrieving or viewing papers and objects toward the back of a desktop or tabletop is extremely difficult for WC users [1,3].

A wheelchair-mounted camera system, called the WC camera, was developed to increase a power WC user's ability to peer forward, which is important for many educational and occupational tasks as well as daily living activities (Fig. 2(*c*)). There are 1.6 million wheelchair users in the United States. About 45% of wheelchair users are under the age of 64 [4]. Thus, visual limitation as a consequence of being in a wheelchair is a problem that affects a large number of employment-age Americans. Past literature has focused on improved wheelchair mechanics, ergonomics, and seat positioning. However no mention of an engineering approach to solve WC attributed visual impediments could be found.

The design and development of the WC camera were based on the requirements of a quadriplegic power WC user and a decision matrix by evaluators. The factors of safety and failure modes and effects analysis (FMEA) were performed to determine the reliability and durability of the device and ensure the safety of the user. A House of Quality (HOQ) was performed to determine if this device satisfied the requirements of a power WC user with limited upper mobility and if this device would be better than alternative viewing methods. We believe such detailed engineering analyses are crucial prior to empirical testing of the WC camera by power WC users in different settings and situations [5].

2 Design Approach

2.1 Human Factors of Client. The initial design concepts for a WC vision aid were based on the needs of a client, who was interviewed several times during the design phase. The client was a spinal cord injured person using a power WC with limited arm mobility but no hand motor skills. Several design constraints for the device were generated. The vision aid (1) had to be operable using no or minimal hand and arm functions, (2) could not interfere with WC functions or movements, (3) must not exceed the dimensions of the WC when retracted, and (4) had to be reliable. During client consultations, it was determined that a vision aid for forward viewing was more necessary than rear or lateral viewing.

The power WC that was used during the device development was a Permobil® electric wheelchair (Lebanon, TN) with automatic seat functions, including recline, tilt, and elevator. These features affected where the device should be placed. The client required to transfer into and out of the WC unobstructed by the device. Additional freedom of movement could be achieved using commercial digital cameras with lens that automatically rotated left and right and tilted up and down. A Quickcam® Orbit™ camera (Logitech, Inc., Freemont, CA) was used, which also included pan, zoom, and autofocus.

2.2 Quality Function Deployment. In addition to the client's personal requirements, a panel of five evaluators identified additional design requirements for power WC users for quality function deployment (QFD). A HOQ was performed by taking the list of customer requirements, ranking them according to importance, and relating them to engineering requirements for designing the vision aid (Appendix A). The most relevant engineering charac-

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Manuscript received March 4, 2008; final manuscript received August 20, 2008; published online November 19, 2008. Review conducted by Ted Conway.

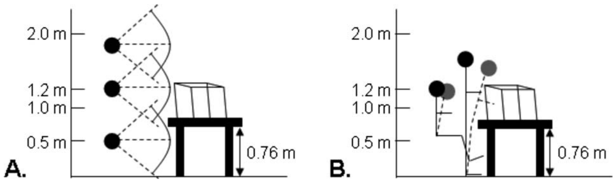

Fig. 1 Anthropometrical data put the average eye height of standing males to be 1.75 m. The average eye height of male power WC users is 1.20 m [1,2]. In (*a*), the eye heights of someone standing, sitting in a wheelchair, and lying down are represented by top, middle, and bottom black dots. Lines of sights projected from these eye heights are shown. All three eye heights are possible by a nondisabled person; however, a WC user is restricted to viewing from a single sitting position height (middle black dot) that prevents seeing over objects or looking underneath standard height tables. (*b*) shows the extent WC users can lean forward to peer into or over objects. Standing persons can peer further because of their greater ability to lean forward and height advantage. In this example, the WC user cannot get closer to the container due to obstruction of the WC user's footrests.

teristics were assigned a weight value (5 = most relevant). For instance, the customer requirement, " does not inhibit user," was linked most closely to the engineering requirement, "number of functions" in which the device "inhibited" the user; "ease of deployment" was linked to the "number of steps to deploy;" "good view enhancement" was linked to the "number of views;" "safety" was linked to the "factor of safety of the material;" and "resiliency" was linked to the "number of environments" the device could withstand (e.g., heat, rain, or snow).

The significance of respective engineering requirements was determined by a technical importance rating (TIR) (Appendix A). The TIR was calculated by multiplying the rankings for each customer requirement by their customer rating and then adding them. High TIRs indicated which engineering requirements were most important to the customer. Weight, range of height and extension, number of inhibited functions, and material strength were the top five most important engineering requirements related to satisfying the greatest amount of customer requirements.

2.3 Design Concept Options. Design concepts readily focused on placing a telescoping arm holding a digital camera on the WC backrest behind the person or mounted near or on the armrest, because these positions accommodated transferring into and out of the WC did not impede WC features and provided the required vision needs.

Different mechanisms were investigated to produce the telescoping arm. One concept utilized the mechanical movement of a scissor lift. The advantages of the scissor lift were the one degree of freedom (DOF) mechanism and being a complete solid linkage structure. The disadvantages were that it must be actuated in a linear path and that trajectory required positioning in an angular direction to achieve a further line of sight, which would require two DOFs.

Another design concept mimicked an adjustable desk lamp. The adjustable desk lamp design would use coulomb friction to position and stabilize the device in multiple DOFs. However, this mechanism disallowed automated use, storage, and adjustability.

The third mechanical concept was a belt-driven mechanical linkage with a single rotational input (one DOF) mounted on the backrest near the armrest of the WC. This mechanism allowed for variations in vertical and horizontal camera positioning as it moved between fully retracted and fully extended positions. This design was selected as the final design and referred to as the WC camera (Fig. 3).

Fig. 2 The body mechanics of sitting in a WC makes forward viewing problematic because of their low height and the difficulty to direct one's eye line at the object of interest. (*a*) A WC user attempts to peer inside a water bath on a cabinet-style laboratory bench. Without feet and knee clearance, (*b*) demonstrates the typical sideways posture of a WC user to get close enough to look inside a water bath on a hot plate. This posture can cause neck and back strain over time as well as safety concerns, such as positioning one's face close to the hot water bath. (*c*) The WC camera permits viewing inside the water bath without having to strain the body to get near. Real-time camera viewing through a laptop PC also permits images and video to be recorded.

2.4 Failure Modes and Effects Analysis. A failure modes and effects Analysis (FMEA) for each part of the WC camera was used to identify and rank potential failure modes so preventative actions may be taken during the design process to ensure im-

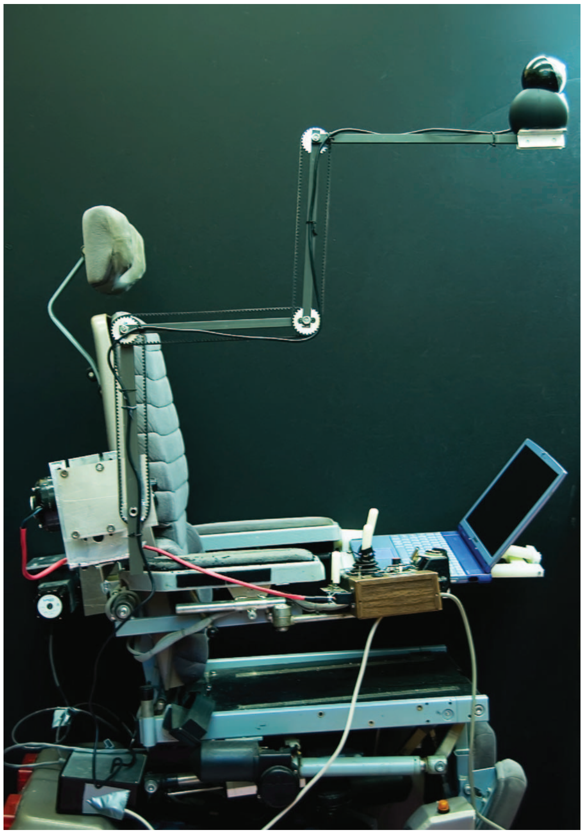

Fig. 3 Lateral view of the prototype WC camera mounted above the armrest of a power wheelchair. This location does not interfere with the movements of a WC user or the functions of the WC. When the device is retracted, the user is able flip up the armrests to transfer from and into the WC. In this view, the device is rotated 90 deg placing the digital camera slightly above eye height.

proved reliability and safety (Appendix B). The belts were found to be most critical to proper functioning because of the risk of the belt rubbing on jam nuts attached to the flange. In addition, if too much load were placed on the system, over time the belts would likely be the first to break. If a belt broke, the whole mechanism would fail. The ground flange was found to be the second most critical part because the ground pulley and the motor were mounted directly to it. It was important that the shaft be concentric with the center of the hole in the ground flange and has strong construction and connections. If the ground flange broke, the device would also be inoperable. In the event of an overload due to lateral force at the tip of the mechanism, the mechanism would fail by belts slipping off the surface of the pulley or by shearing of the retainer clips connecting the input link to the motor shaft. With the exception of the failure case involving retainer clips, the device would collapse vertically in a rapid manner. During retainer clip failure under lateral load, the user could be at risk of injury due to possible lateral motion of the failing device.

3 Device Development

3.1 Position Analysis of Arm. The basic design consisted of four rigid links pinned together to form a movable arm with a digital camera attached to the tip of the fourth link. Each link had pulleys rigidly attached, as shown in Fig. 4(*a*). Three flexible belts attached to the pulleys between pairs of links constrained the motion between these links allowing the device to be driven by a single input (Link 1). Figure 4(*b*) shows a schematic of the assembled device and the belts, which connected links via the pulleys.

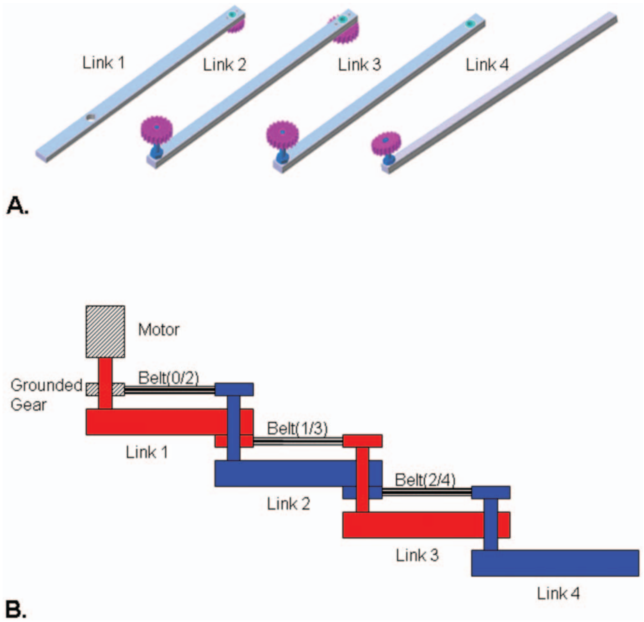

Fig. 4 Drawings of the individual link subassemblies are shown (*a*). Link 1 has a keyed hole through which a drive shaft transmits torque from the motor; on the opposite end of Link 1, there is a pulley screwed onto it with a bushing in the center. A threaded pin on Link 2 passes through the bushing on Link 1 and rigidly connects a pulley to Link 2. On the opposite end of Link 2 is a pulley screwed onto it with a bushing in the center. A threaded pin on Link 3 passes through the bushing on Link 2 and rigidly connects a pulley to Link 3. Finally, on the opposite end of Link 3 there is a bushing through which a threaded pin on Link 4 passes and rigidly connects a pulley to Link 4. (*b*) An assembly view of the device is shown with belts spanning the pulleys driving the rotation of the links.

The operation of the mechanism was determined by the kinematic constraints of the design. With inextensible belts, no slipping occurred between pulleys and belts, and tension was maintained throughout the entire range of motion. Pairs of belted links separated by a pulley support link were kinematically constrained to remain parallel to each other as they moved since the pulleys were of equal radius. For example, Links 2 and 4 attached to supporting Link 3 are initially aligned parallel to each other. Rotation of Link 2 with respect to Link 3 causes Link 4 to rotate the same amount and in the same direction relative to Link 3, hence Links 2 and 4 remain parallel. Thus, as shown in Fig. 4(*b*), the following links connected by belt and pulleys were constrained to remain parallel:

1. Link 0 (ground) and Link 2 connected by belt (0,2)
2. Link 1 (input) and Link 3 connected by belt (1,3)
3. Link 2 and Link 4 (output) connected by belt (2,4)

The web camera was attached atop the end of Link 4, which travels along a semicircular path as the input (Link 1) is rotated from 0 deg (fully extended) to 180 deg (fully retracted). Therefore, the camera could be positioned upright anywhere along this path. The tip of Link 4 reached a maximum height of 20.3 in. above its point of attachment and extended forward 43.75 in. from the base using link lengths of 10.15 in. for the first three links and a length of 13.3 in. for Link 4 (Fig. 5).

3.2 Static Force Analysis. The primary loads on the mechanism were the weights of the links, the digital camera, and the belt-pulley systems. The weights of Links 1, 2, and 3 were multiplied by a factor of 2 to compensate for the extra mass of the

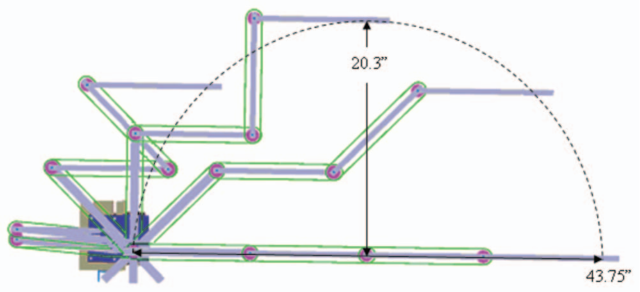

Fig. 5 Five different positions of the WC camera are shown spanning a continuous range of the input link from 0 deg to 180 deg. These various positions are important for viewing in different situations.

belt-pulley systems. Static analysis was performed, assuming that the speed of the mechanism would be insufficient to induce significant dynamic loads. Free body diagrams (FBDs) were completed in order to analyze these forces (Fig. 6). The belts were treated as having finite tensions $F_{p--,t}$ and $F_{p--,s}$ at both points of tangency on the pulleys. Timing-belts were used to transmit torque between the pulleys in order to alleviate pretension loads on the pins and links caused by friction pulleys. For the static force analysis, this implies that one side of the belt will have positive tension, while the other has zero tension.

Moments were summed about the center of the pin joint nearest to the motor for each link in order to compute motor torque as well as belt torque on pulleys. In the equations below, the ith link length is denoted by r_i in the pulley radii and is denoted by R_p. The torque on the pulleys connecting Links 2 and 4 are shown to be constant with respect to the input angle. The FBD of the output Link 4 showed that the only moment to overcome the gravitational moments was torque due to belt tension (Fig. 6). Since Link 4 was constrained not to rotate as the input rotated, the moments due to gravitational force were constant. Thus, the belt torque would be constant too, as reflected in

$$T_{p24} = (F_{p24,t} - F_{p24,s})R_{p24} = m_4 g r_{\mathrm{CM},4} + m_{\mathrm{load}} g r_4 \tag{1}$$

In a similar manner, the belt torque on the pulleys connecting the ground and Link 2 was constant with respect to the input angle, as given in

$$T_{p02} = (F_{p02,t} - F_{p02,s})R_{p02} = T_{p24} + m_2 g r_{\mathrm{CM},2} + (m_3 g + m_4 g + m_{\mathrm{load}} g) r_2 \tag{2}$$

The torque exerted by the belt connecting Links 3 and 1 was proportional to the cosine of the input angle θ_1 since the gravitational loads on the two links have a moment arm that varied proportionally to the cosine of the input angle (Fig. 6). Thus, the belt torque was dependent on the gravitational loads. This is reflected in Eq. (3), which was the result of summing moments.

$$T_{p13} = (F_{p13,t} - F_{p13,s})R_{p13} = m_3 g \cos(\theta_1) r_{\mathrm{CM},3} + (m_4 g + m_{\mathrm{load}} g)\cos(\theta_1) r_3 \tag{3}$$

Lastly the motor torque applied to Link 1 was proportional to the cosine of the input angle as given in

$$T_m = T_{p13} + m_1 g \cos(\theta_1) r_{\mathrm{CM},1} + (m_2 g + m_3 g + m_4 g + m_{\mathrm{load}} g)\cos(\theta_1) r_1 \tag{4}$$

Figure 7 shows reaction torques provided by the belt and the motor for the WC camera mechanism. The masses were $m_1 = m_2 = m_3 = 0.12$ kg, $m_4 = 0.08$ kg, and $m_{\mathrm{load}} = 0.27$ kg; the center of mass locations $r_{\mathrm{CM},-}$ were half of the link lengths.

3.3 Component Specification Based on Load (Belts, Links, Pulleys, and Pins). The belt chosen to support tensile loads, based on manufacturer's load ratings and size, was a 5 mm pitch HTD 6 mm wide belt made of neoprene with fiberglass cords. The torque ratings for the belts were based on pulley speed and size. Since the effect of speed in this mechanism was negligible, the pulleys were selected to have a pitch diameter of 39.8 mm, though the loads on each of the belts varied. With the belts having an allowable torque of 4.2 N m, the factors of safety for the belt connections at linkages 0 to 2, 1 to 3, and 2 to 4 were 1.8, 4.1, and 4.1, respectively.

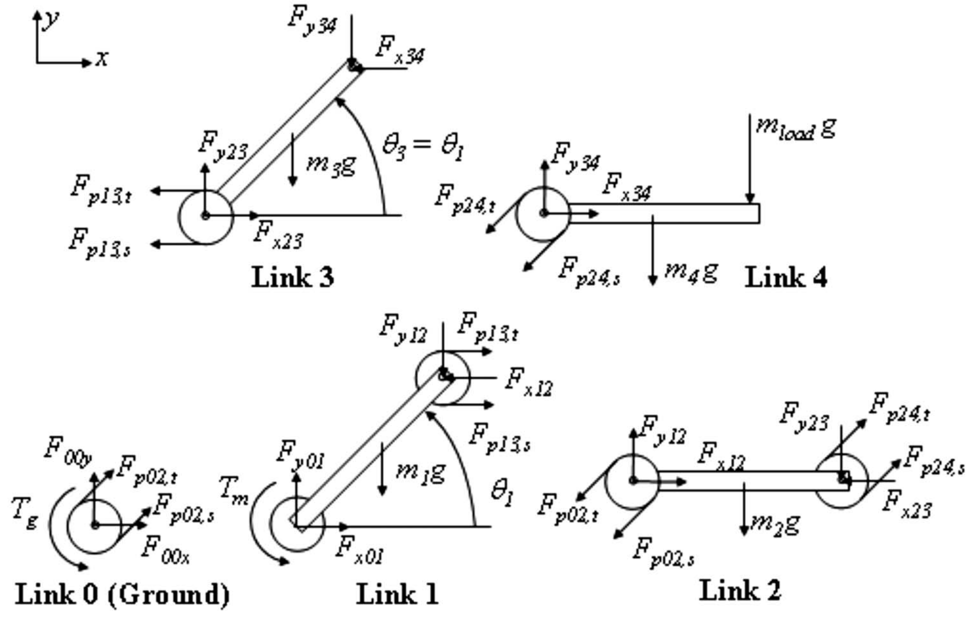

Fig. 6 Free body diagrams are shown for each link in the mechanism

The bending stresses for the links in the WC camera were cal-

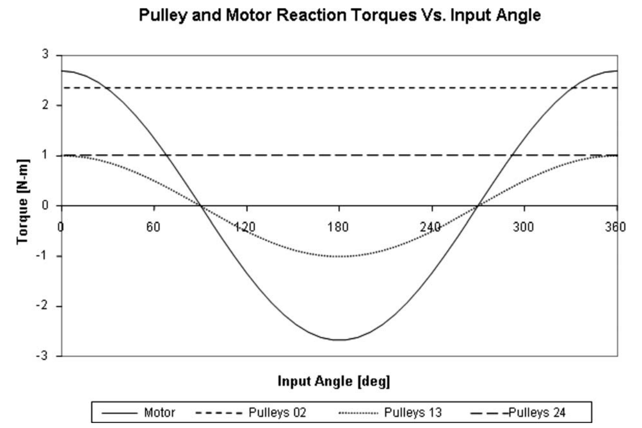

Fig. 7 The reaction torques transmitted between belts and pulleys as the input angle changed from 0 deg to 360 deg, though rotation past 180 deg was rarely performed for viewing purposes

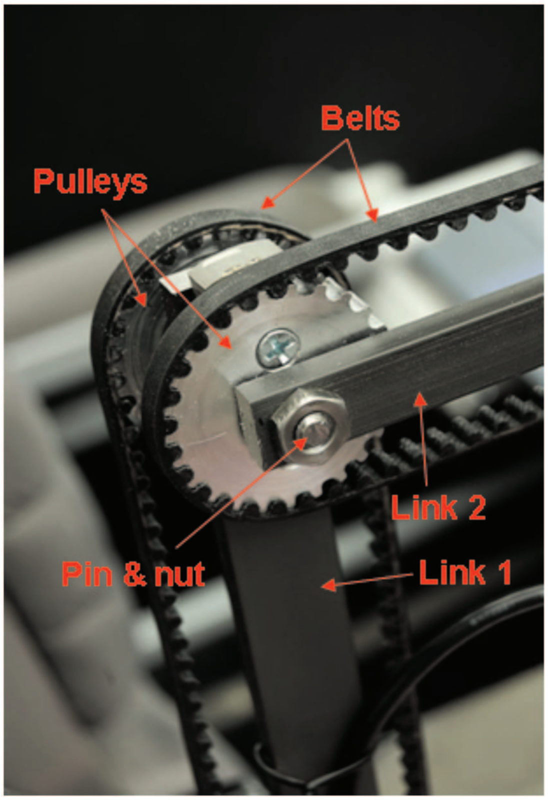

Fig. 8 A close-up view of the mechanism showing the connection between Links 1 and 2. The pulley in the background attaches to and rotates Link 2 by the pin and nut. The pulley in the foreground is attached to Link 1.

culated at the critical section, which was at the base of each link. The bending moment was verified to be the greatest at the point farthest from the digital camera. The use of links with a high aspect ratio cross section made shear stresses negligible, and an Euler buckling analysis showed that buckling was not an issue in either direction perpendicular to the link's axis. To check for buckling, the maximum force in the longitudinal axis of each link was compared with the critical Euler buckling load for the given cross-sectional area moment of inertia, elastic modulus, and length considering free end conditions. Bending stress was calculated by considering a reduction in area moment of inertia due to bushing and shaft holes at the critical sections. Cross-sectional areas for the links were thus chosen to be Link 1 (0.75×0.50 in.^{2}) and Links 2, 3, and 4 (0.50×0.25 in.^{2}), and the material chosen was 6061 aluminum alloy. Threaded pins based on the yield criteria were coupled with jam nuts to allow for adjustment and spacing between links (Fig. 8). The pulleys were fixed axially and angularly relative to links.

3.4 Electrical Specifications of WC Camera. The motor driving the WC camera was activated with a power button. A toggle switch for forward and reverse motion of the WC camera arm changed the direction of rotation of the ground link. The WC camera controls were located near to the wheelchair joystick for easy access by the user. Other controls may be used to better suit each user's specific preferences, including control from a wheelchair-mounted PC.

The essential electrical components of the motor were housed in a control box mounted on the plastic shell of the wheelchair backrest above the right armrest. For the prototype, 120 V ac power was used; however, power can be provided by the two 12 V wheelchair batteries or an alternate 12 V, 7 A dc battery source. The gear motor used to power the device was capable of providing 4.6 N m of torque, which easily turned the assembly. A worm gear within the motor assembly enabled static locking of the deployed device in the absence of power.

4 Evaluation

4.1 WC Camera Features. The WC camera extended the height and forward viewing ability of a power WC user. The user could adjust the angle of Link 1 of the mechanism from 0 deg to 180 deg to vary the height and reach of the tip to provide numerous viewing positions. When Link 1 of the WC camera was oriented 90 deg to its base, the tip of the arm was at its greatest height. This placed the digital camera 20.3 in. high from the base, slightly higher than the average WC user's eye height [1,2] in the same vertical plane as the wheelchair's footrests (Fig. 3). This provided the user the same line of sight as someone standing. When the WC camera extended forward, the WC user's eyesight was able to virtually lean forward and peer over obstacles.

When Link 1 was positioned at 0 deg, the arm became completely horizontal, extending the tip 43.75 in. from the torso of the WC user. This positioned the camera almost 2 ft past the WC user's knees, farther than the average WC user's reach [1,2]. Though at this position the camera height was near the user's waistline, the WC camera was able to view over wide expanses, such as across desktops or over ledges. Angling the lens of the camera downward was also important for peering over and into objects.

4.2 HOQ Comparison to Existing Products. Another important aspect of the HOQ was to compare the WC camera to similar commercially-available camera holding devices concurrent with the design process (Appendix A). A comparison to a data could not be achieved because a suitable prior or commercially-available vision aid for WCs could not be found. The Quik Pod™ (Fromm Works, Inc.) and Magic Arm (Adaptavation, Inc., Sioux Falls, SD) were not automated; however both products allow users to extend camera viewing from their bodies or WCs. Due to their similarities in function, their ratings and specifications were used to determine target (delighted) values for comparison.

The HOQ showed that the WC camera design met or exceeded 8 out of 17 targeted engineering specifications. These eight achieved specifications, which included the four top-ranked engineering requirements identified through the TIR, were range (height and extension), compatibility to different WCs, number of functions inhibited, steps required for deployment, number of views possible, displacement, and weight (Appendix A). Some specifications could not be measured during this development phase, including people who liked the look of the product, number of environments, and duration of warranty. Also, some specification target values could be met if greater resources were available. For instance, stronger material or a motor with lower power requirements could have been used. Likewise, price could be reduced with changes in material.

5 Conclusions

A quadriplegic wheelchair user due to a spinal cord injury presented to engineers this problem of limited line of sight. We believe the WC camera is the first device to address providing greater visibility for power WC users. The aims of this project were to answer questions whether a vision aid could be developed to satisfy the ergonomics of an active power WC user, how it should be designed, what features to offer, and what possible benefits it could provide WC users.

As recommended by Childress [5], the design of the WC camera considered both the practical needs of the user and theoretical engineering analyses. The human factor requirements of the client were satisfied by the final design. The device was operable without hand dexterity and did not impede the power WC functions, which included automatic backrest recline, seat tilt, footrest extension, and seat elevation. The WC camera also did not hinder the ability to transfer into and out of the wheelchair. The stress and load modeling and the FMEA dictated how the WC camera should be made and what preventative actions should be taken to ensure proper functioning.

When in a sitting position, the WC user's lower extremities force one's eye line farther back from obstructions that lack knee clearance, such as railings and cabinets. Positioning the WC camera between upright and horizontal permitted the WC user to peer into deep containers placed on a table or other raised surface. This would be critically important for watching a pot boil or to looking at a car engine to peering inside the body cavity of a cadaver on an examining table during a gross anatomy course. We believe the use of the WC camera by power WC users in different occupational, educational, and daily living settings would expand its application and improve its design.

A likely improvement to the device could be made by using high-strength light-weight materials for the links, pulleys, and joint components. The weight of these components was the major load on the mechanism. Also, frictionally induced loads would be less significant if the component weights were reduced. Lesser loads would require lower input power to the system, decreasing system cost and increasing reliability. In addition, a smaller motor could be used to generate the same amount of torque as the one used here, while decreasing overall system weight and size.

The WC camera was mounted on the rear of the WC, but different mounting positions are possible. For this particular case, the mounting location was largely dependent on the mobility requirements and preferences of the WC user. Likewise, the position of the switches can also be relocated based on the user's needs. We believe that with further testing and development the WC camera could be an important assistive technology device for power wheelchair users.

Acknowledgment

The authors thank Luis Moreno and John Cirillo for their contribution to this project; we are also grateful to Ed Kinsel for valuable discussions about mechanism design. We appreciate the participation of David Groves, Samia Twainy, Rakesh Jayakumar, and Aditya Singhal. Special thanks to Bert Gramelspacher for his timely help with electronics and Michel Schweinsberg for expert photography.

Appendix A

Table 1 presents the WC camera specifications.

Table 1 House of Quality for WC camera was performed to relate the customer needs to engineering specifications for designing the vision aid. The WC camera specifications were compared with target values and similar commercial products. TIR=technical importance rating. 5=most relevant.

WHO							HOW (ENGINEERING REQUIREMENTS)																	NOW	
Customer (TIR Ratings)	Customer	Manufacturers	Sales				Range (height)	Range (extension)	Wheelchair compatibility	Volume required	No. of functions inhibited	Steps (deploy)	Number of views	Displacmnet	Years of warranty	Factor of safety	Required power	Strength of material	No. of environments	People that like the look	Weight	Steps (assembly)	Price	Quickpod	Magic Arm
6	12	13	11	WHAT (CUSTOMER REQUIREMENTS)	Adjustability	Good Range of Height	5	1		1		1		1			1			1	3			2	2
7	11	12	12			Good Range of Extension	1	5		1		1		1			1			1	3			3	2
1	17	14	5			Compatible to different WCs			5	5	3											3		1	3
9	9	15	6			Compact (installed)				5											1			1	3
14	4	16	15			Does not inhibit user	1	1		1	5													3	3
16	2	11	7		Performance	Ease of deployment	3	3		1	3	5					5				5			1	1
17	1	17	2			Good view enhancment	5	5					5											4	3
11	7	4	16			Stable	1	1						5				3			5			3	3
12	6	5	8			Reliable									5									3	3
15	3	1	10			Safety				1	5			1		5		5			3			3	3
2	16	10	17			Min. power requirements	1	1				5					5				5			1	1
10	8	6	14			Durable								3				5						3	3
13	5	7	13		Other	Resilient													5					3	3
5	13	9	4			Looks good	1	1		1										5				3	3
3	15	8	9			Light weight				1							3				5			3	3
4	14	2	3			Simple assembly	1	1		3		3									5	5		4	3
8	10	3	1			Low price											3						5	5	1
						TIR	206	210	5	128	196	115	85	113	60	75	136	158	65	38	273	23	40		
				NOW		Units	in	in	#	in^3	#	#	#	in	#	N/A	W	Kpsi	#	%	lbs	#	$		
						QuickPod	24	24	0	12	1	1	inf	N/A	0.08	N/A	N/A	10	2	90%	1	1	25		
						Magic Arm	6	6	90%	12	0	1	inf	N/A	1	N/A	N/A	10	1	90%	3	1	121		
						Target (Delighted)	20	20	95%	12	0	1	inf	0.5	5	2	7A/12 V	200	3	90%	2	1	80		
						Achieved	20	43.8	99%	24	0	1	inf	0.5	-	-	36A/115V	40	-	-	2	3	230		

Appendix B

Table 2 presents the components of the WC camera and their respective FMEA.

Table 2 Listed are the components of the WC camera and their respective FMEA. The most important and critical parts were determined to be in the following order (most important to least): belts, ground flange, support system, links, web camera, pulley, and motor. The common effect of the failure modes was the failure of the entire WC camera. However, measures can be taken to prevent mechanical damage from occurring by stabilizing the system by tightening connections and checking stress points. Using stronger materials is another way of ensuring proper functioning.

Part	Function	Failure mode	Effect of failure	Potential cause of failure	Possible means of detection	Preventive actions to be taken
Motor	Provides torque to lift system	Does not provide sufficient torque	Mechanism will not move or be unstable and will fall	Too much weight; electrical surge	Torque analysis; inspection	Powerful motor and fuse in elec. path
Support system	Supports complete system to wheelchair	Does not support system to wheelchair	Mechanism will fall	Too much weight/fatigue; small crack prop.	Stress analysis; inspection	Use strong material; triangular supports
Flange	Provides a ground link to mechanism	Does not support ground pulley	Mechanism will fall	Loose jam nuts; bending, fatigue	Stress analysis; yielding/deflection	Tight jam nuts, strong flange material
Links	Lifts webcamera	Does not lift webcam	Links break; mechanism falls	Thin, weak material; weight overload, galling	Stress analysis	Strong material care in manufacturing
Pulleys	Provides supports for belts to lift links	Does not support belts	Pulley pins shear	Too much stress on pulleys; loose connection of pulley	Visible inspection	Tighten connections
Belts	Provides tension on pulleys to lift links	Does not provide tension to lift links	Belt tears/breaks; Belts fall of track	Ripping due to overload; ripping due to rubbing	Spacing from drawings	Specified belts for torque ratings
Webcam	Provides user with an extended view	Does not produce image to user	Loss of power to camera; camera falls off	USB disconnected; camera exposed to outside force	Camera turns off; image does not come up	Secure mounting and connection for camera

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